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REPORT OF INVESTIGATIONS/1989

Effects of Structural Faults on Ground Control in Selected Coal Mines in Southwestern Virginia

By Gregory M. Molinda and David K. Ingram

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	in	inch
ft/d	foot per day	pct	percent
h	hour	st	short ton

EFFECTS OF STRUCTURAL FAULTS ON GROUND CONTROL IN SELECTED COAL MINES IN SOUTHWESTERN VIRGINIA

By Gregory M. Molinda[1] and David K. Ingram[1]

ABSTRACT

Large structural faults create serious ground control hazards, as well as adversely affect coal mine production. Two faults related to the Pine Mountain overthrust sheet in Buchanan County, VA, were investigated by the U.S. Bureau of Mines to determine their effect on ground control and to develop recognition criteria for prediction. Five underground mines encountering these faults were visited and mapped for structural information. This information, along with surface mapping, indicated that Pistol Gap and Keen Mountain Faults show right-lateral, strike-slip faulting and bedding planes slippage, which can be projected linearly and vertically. These fault zones are up to 200 ft wide, with coalbed offsets up to 18 ft vertically, coalbed swags (depressions) up to 15 ft, and roof falls up to 20 ft high. Recognition criteria include bedding plane slips, coalbed offsets, fault gouge, coalbed swag (depressions or synclines), and disturbed bedding. These recognition criteria will help an informed operator realize that many sudden coalbed discontinuities are related to larger geologic events (in this case thrust faulting) and can be projected linearly and vertically. Ground control strategies include mine designs that minimize fault exposure. Mining plans can be adjusted based on type and extent of fault movement.

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INTRODUCTION

Faults may be defined as breaks in the horizontal or vertical continuity of a rock where there has been movement parallel to the fracture plane. Faults can develop for a number of reasons, ranging from local readjustments of strata boundaries related to surface loading, to regional strata failure related to plate tectonics. Most coalbeds have faults affecting their continuity, but these faults are usually on a local scale and reflect local warping associated with overburden loading before rocks were lithified. Other faults are a result of the stresses associated with major crustal movement and affect more than one stratum, and perhaps a large section of strata.

A fault or fault zone in a coalbed can cause serious safety and production problems when encountered by a development section. In reality, a fault usually occurs as a series of fault surfaces rather than the single planar surface commonly portrayed. Faults can be of several types: normal, due to tension; thrust and bedding plane, due to compression; strike-slip, from shear forces; or normal, reverse, and strike-slip (a combination of the above) (fig. 1). Fault planes can be straight, curved, hinged, stepped, or discontinuous. Many times the planes dip in opposite directions and have a range of orientations about the main trend. Opposite-dipping fault planes can cause the roof to drop out in blocks. Also, the adjacent roof is generally broken up and may contain fault gouge (crushed rock with a claylike texture) throughout the width of the affected zone (up to several hundred feet and more). This fault gouge can be extremely dangerous because it is not self-supporting, weathers easily and rapidly, and is difficult to rock bolt. Conventional rock bolting in a fault zone is difficult because of uncertainty about the shape of the roof blocks that need to be pinned together.

In most instances, the fault is not a clean break. Depending on the direction and magnitude of the stresses responsible for the faulting, the coalbed may be thrust up into the roof (compression), dragged parallel to the fault plane (strike-slip), or pulled apart with one limb down dropped (tension). Because of frictional resistance, the coalbed, at the point of failure, may be severely mangled and will not function as a stable roof member. The type of roof failure and resultant roof control strategy are dependent on the type and magnitude of the movement along the fault surface.

This U.S. Bureau of Mines investigation focused on faults caused by large-scale crustal failure rather than on smaller structural or depositional faults that have only local effects. These large tectonic structural types of faults have a more consistent and predictable nature, allowing the mining industry to benefit by their study. Several well-known faults were selected, and information about their effects on local mining was gathered from mine maps, underground visits, and consultations with mining personnel and Federal safety officials. These faults were observed over their extent in order to document trends, movements, and effects on roof strata over the study area. This information will help mine operators make projections as well as plan appropriate roof support strategies and mine design. This type of information can be particularly useful to small operations (10- to 12-person) with limited reserves. Knowledge of a fault zone before mine layout and design can minimize hazardous mining conditions and production losses. This work was done in support of the Bureau's mission to enhance worker health and safety.

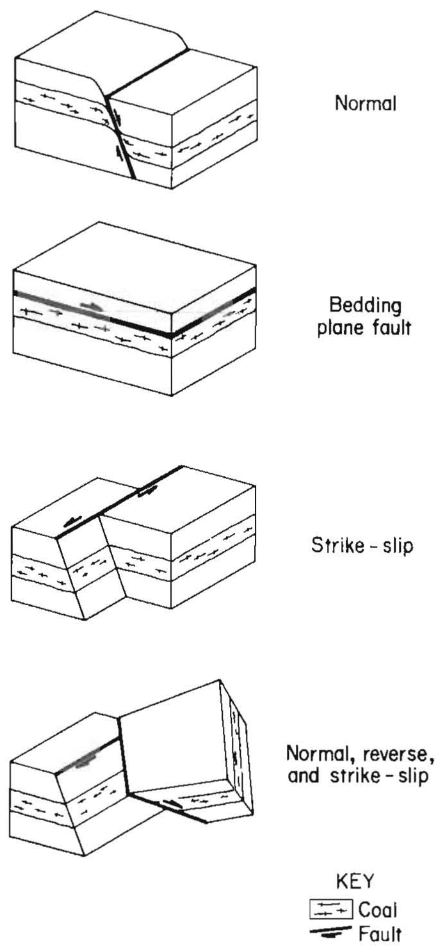

Figure 1.–Types of faults and associated movement.

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The cooperation of Mine Safety and Health Administration (MSHA) District 5 (Norton, VA) personnel, especially Tom McLoughlin, ground control geologist; and Jerry Wiley, coal mine inspection supervisor, is greatly appreciated. The contributions of Bill Copely, Permac, Inc., Oakwood, VA; and David Wampler, United Co., Grundy, VA, which included information, maps, and site visits, are also appreciated.

BACKGROUND

The coalfields of southwestern Virginia were chosen as a study site because of their proximity to the Pine Mountain Overthrust sheet. This area contains one of the most structurally disturbed coalfields in the Eastern Coal Province. The Pine Mountain overthrust sheet is a detached section of crust about 125 miles long and about 25 miles wide, which has been moved, in a northwesterly direction as a slab, up and over existing rock for many miles (*1*).[2] This rectangular sheet is located at the junction of Virginia, Kentucky, and Tennessee in the southern Appalachian coalfield (fig. 2). The Pine Mountain sheet originated as a splay sheet from a larger, deep-seated crustal movement. Movement along the Pine Mountain sheet occurred along the incipient glide plane parallel to bedding in weak shale units. This movement is due to compression oriented northwest-southeast. The sheet became detached when frictional resistance became too great and the fault sheared upward to the surface. The rupture of the crust, bounding the sheet to the northeast, occurred progressively northwestward along the trace of the Russell Fork Fault also during northwestern-southeastern compression (fig. 3). The parallel tear faults (Keen Mountain, Jess Fork, Pistol Gap, and Little Paw Paw), northeast of the sheet, were formed from the same compression.

The overthrust sheet, located near the intersection of the Russell Fork Fault and the Little Paw Paw Fault (fig. 3), was thought to have rotated about a pivot point. As a result of this rotation, the bounding tear faults (Russell Fork, Little Paw Paw, Jess Fork, Keen Mountain, and Pistol Gap) show some secondary compressional overthrusting, as well as the primary strike-slip movement. Lateral movement of the sheet along the tear faults is thought to be greatest (10 miles) near the Jacksboro Fault and least (4 miles) near the Russell Fork Fault (*2-3*).

The area around the well-known Keen Mountain Fault, and what has become known as the Pistol Gap Fault, is the subject of the Bureau's investigation. These two faults

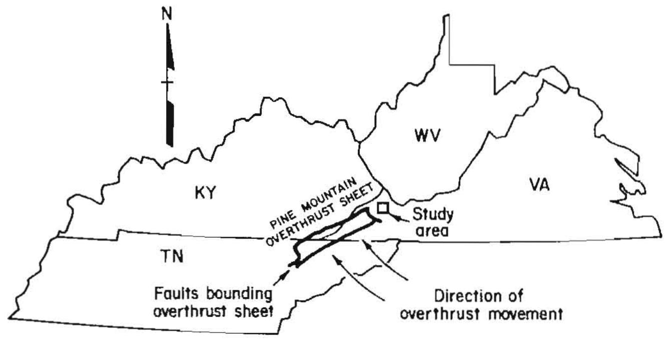

Figure 2.–Location of Pine Mountain overthrust sheet and study area.

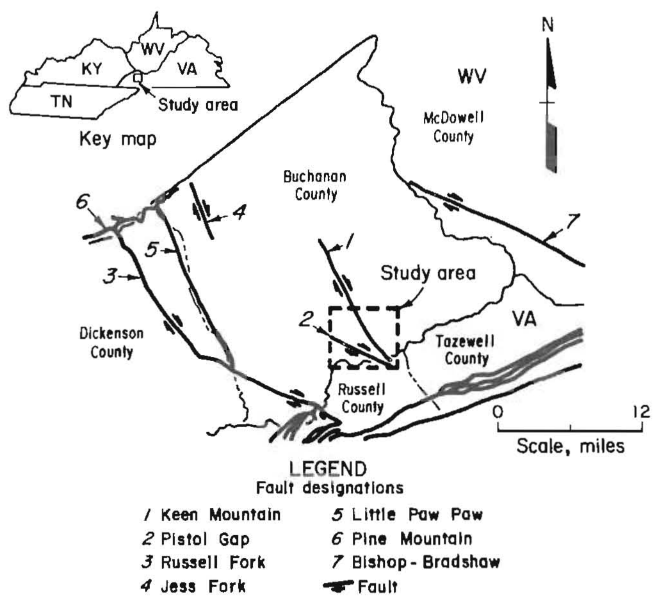

Figure 3.–Structural map of Buchanan County, VA, with study area.

[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

were chosen for study because they are known to seriously affect coal mine roof quality in the area. The Keen Mountain Fault is described as a right-lateral, strike-slip fault with up to 18 ft of vertical displacement observed in an underground coal mine (*4*). Though this fault occurs northeast of the Pine Mountain overthrust sheet, it is considered to have formed as a result of overthrusting and rotation of the sheet itself. It is possible that this fault, and the northwesterly Jess Fork Fault, bounds one of several splinter thrust sheets that may have become detached as a result of the movement of the Pine Mountain overthrust sheet. The Keen Mountain Fault was mapped by side-looking airborne radar (SLAR) imagery and extends northwesterly over a 14-mile distance in Buchanan County (*5*). The effects of this fault have been tracked through a number of underground coal mines and two coal mine highwalls.

Structures like the Keen Mountain and Pistol Gap Faults are readily seen on aerial photographs and land satellite (Landsat) imagery. The Pistol Gap Fault, identified only as a lineament from Landsat imagery, is oriented N. 55° W. and may be an offshoot spur of the Keen Mountain Fault (*6*). It is unknown to what depth these faults extend, but their effect on ground control in minable coalbeds can be documented.

The coalfields of southwestern Virginia have been extensively mined for many years. There are over 30 named coalbeds in the section, with many reaching minable thickness at some location in the area. At the time of this study, there were over 263 underground mines in southwestern Virginia employing over 3,200 miners (*7*). There are five active shaft mines working the Pocahontas #3 Coalbed in the MSHA Richlands subdistrict, which covers the southeastern half of Buchanan County, VA. The remainder of mines are drift entries above drainage.

Most of the mines within the study area that operate one continuous miner section and, rarely, conventional mining sections are small drift operations. On an average, 12- to 20-person work forces are employed in these mines, which have a lifespan of 3 to 5 years.

EFFECTS OF STRUCTURAL FAULTS ON UNDERGROUND MINING IN STUDY AREA

Figure 4 shows the study area with the two faults (Keen Mountain and Pistol Gap) that are affecting mining. The Keen Mountain Fault was originally mapped from SLAR imagery and can be observed in underground exposures and abandoned strip mine highwalls. The Pistol Gap Fault has not been mapped on the surface but is described in this report by underground exposure. The following are examples of the areas where these faults have affected mining.

FALCON FUEL MINE

The Falcon Fuel Mine, a contract mine to United Co., has been severely affected by the Keen Mountain and Pistol Gap Faults (fig. 4). This mine works the Jawbone Coalbed.

The Falcon Fuel Mine is truncated to the northeast by the Keen Mountain Fault. At location A, a seven-entry section was terminated by the truncation of the coalbed against the fault (fig. 5). Poor roof conditions and lack of coal are reported by the operator to be the causes of termination. The other development that intersected the fault is at location B (fig. 5). This five-entry section stopped against the fault trace. Exact conditions of disruption are unknown because all of the eastern developments are sealed to entry and are inaccessible for observation.

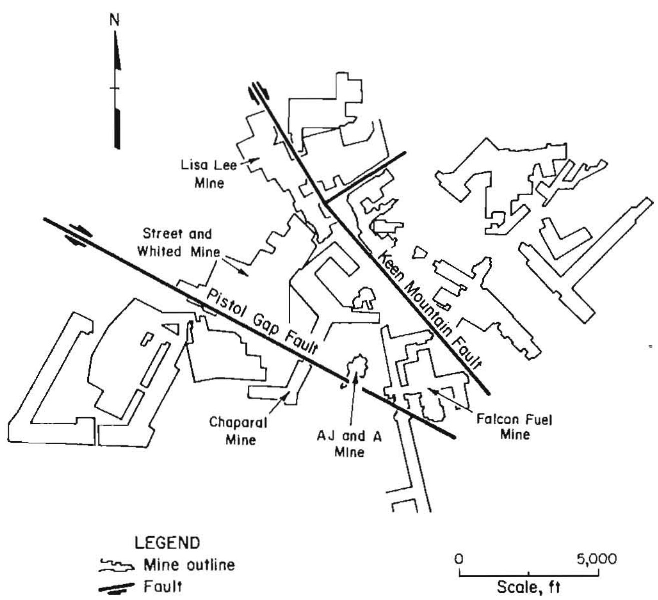

Figure 4.–Mines in study area affected by Keen Mountain and Pistol Gap Faults.

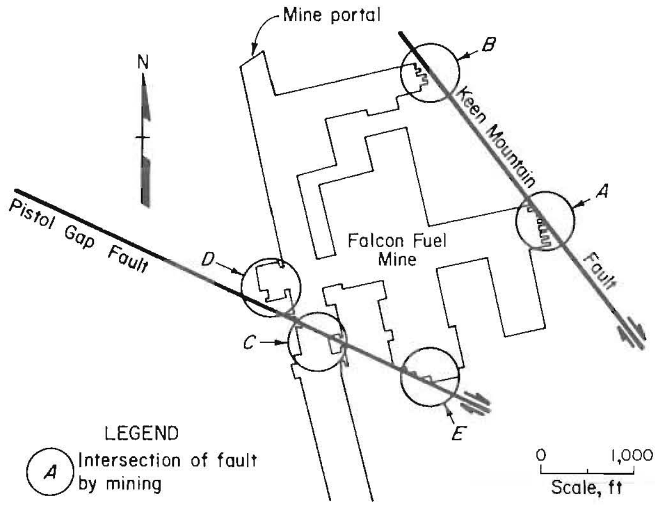

Figure 5.-Falcon Fuel Mine with developments affected by Keen Mountain and Pistol Gap Faults (circled).

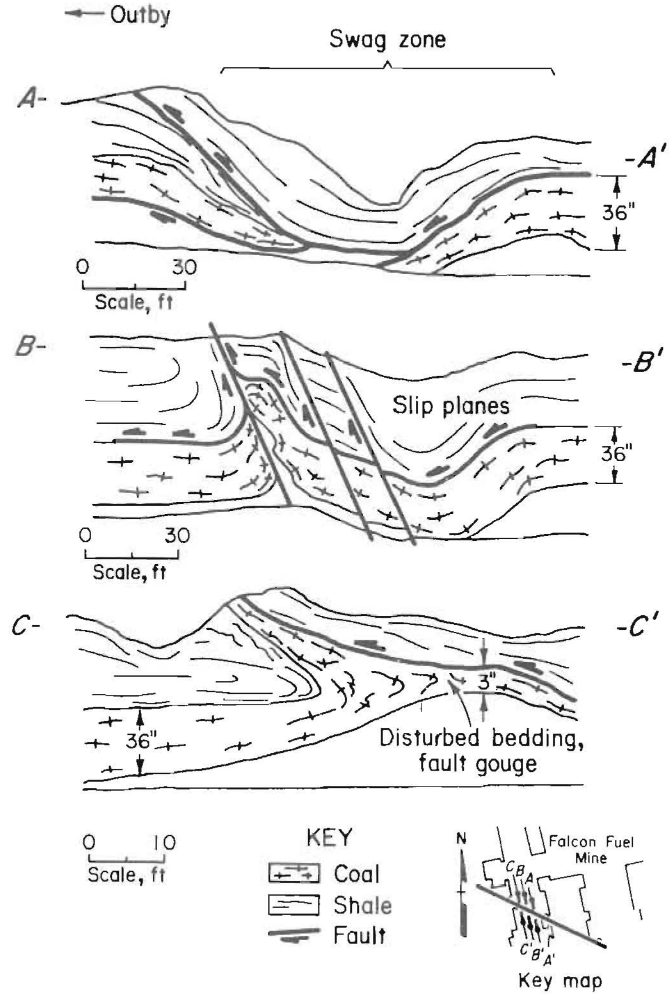

Figure 6.-Series of cross sections of Pistol Gap Fault exposed in Falcon Fuel Mine.

At approximately 2,800 ft inby the portal, the mine first encountered the Pistol Gap Fault (figure 5, location C). The operators withdrew because of adverse roof conditions and began driving a four-entry development to the southwest (figure 5, location D). After approximately 400 ft, the development was halted as the mine again intersected the Pistol Gap Fault zone. The operators did not know at the time that the two discontinuities were the same fault zone. The southwestern development was discontinued and developments were begun to the east.

Mapping at location C indicates that compressive forces oriented northeast-southwest have caused downbuckling of the coalbed and a thrust fault-type failure in the coal and roof strata (fig. 5). Figure 6 (cross section A-A') shows that the fault runs along bedding (roof and coal interface) from A' to A until it reaches the failure zone where it turns up into the roof. Figures 7 and 8 show the coalbed thrust upward, causing a 4-ft-high roof fall (all double figures show geologic structures outlined and labeled because of the difficulty in discerning these structures). In addition, the coalbed is squeezed out to only a few inches by bedding plane movement. In figure 6 (cross section A-A'), the slippage, both at the roof-coal interface and at the floor-coal interface, has completely truncated the coalbed. Highly polished slickensides on roof shales indicate slippage along the roof-coal interface (fig. 9). Slippage occurred along bedding within the roof shale as well as within the coalbed.

At cross section B-B' (only 50 ft away), the nature of the disturbance is different (fig. 6). Here, the compressive forces have dragged the coalbed into the roof and partially severed it. A series of three main faults have isolated two fault blocks, which have been uplifted as horsts. The coalbed and adjacent strata have been severely disturbed between the fault planes (coal fragmentation, fault gouge, and cleat rotation). The mine operator notes that roof bolts have been sheared in the vicinity of the fault, indicating active bedding plane movement since bolt installation. The movement, which has caused bolts to be sheared, appears to be mining induced and not the result of active tectonic compression. The entire mine is above drainage and therefore not subject to farfield horizontal stresses. In both cross sections A-A' and B-B', the Jawbone Coalbed has been overturned because of compression. Also, at all three places where the fault is exposed, horizontal (strike-slip) movement is indicated by slickensides. Roof conditions in the three accessible entries were poor for nearly 200 ft, with falls averaging 8 ft high and extending up to 20 ft high (fig. 10). Supplementary roof support included heavy crossbar sets, posts, I-beams, and resin bolts longer than 8 ft.

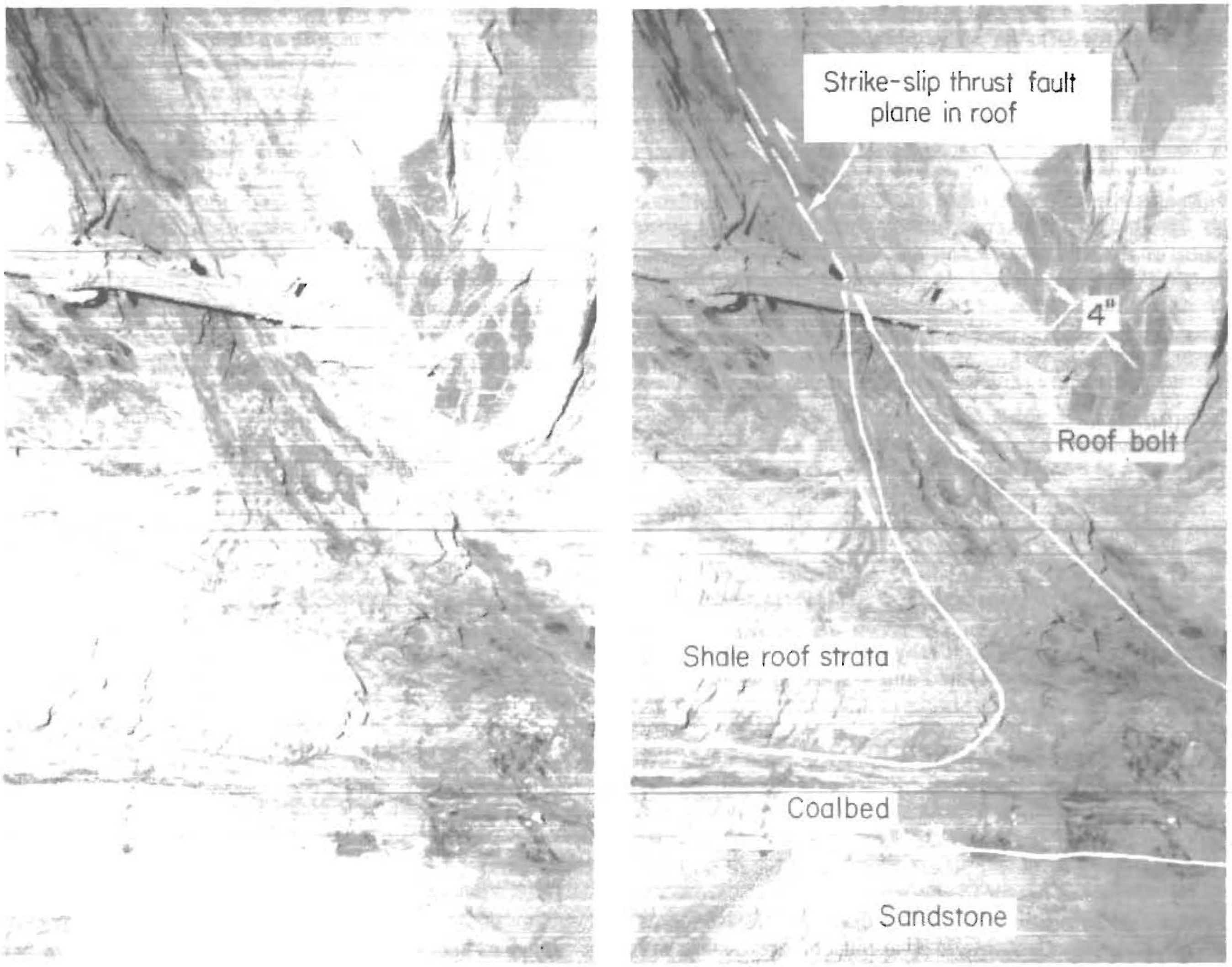

Figure 7.-Severe strata deformation and unstable roof caused by Pistol Gap Fault. Coalbed overturned and dragged upward.

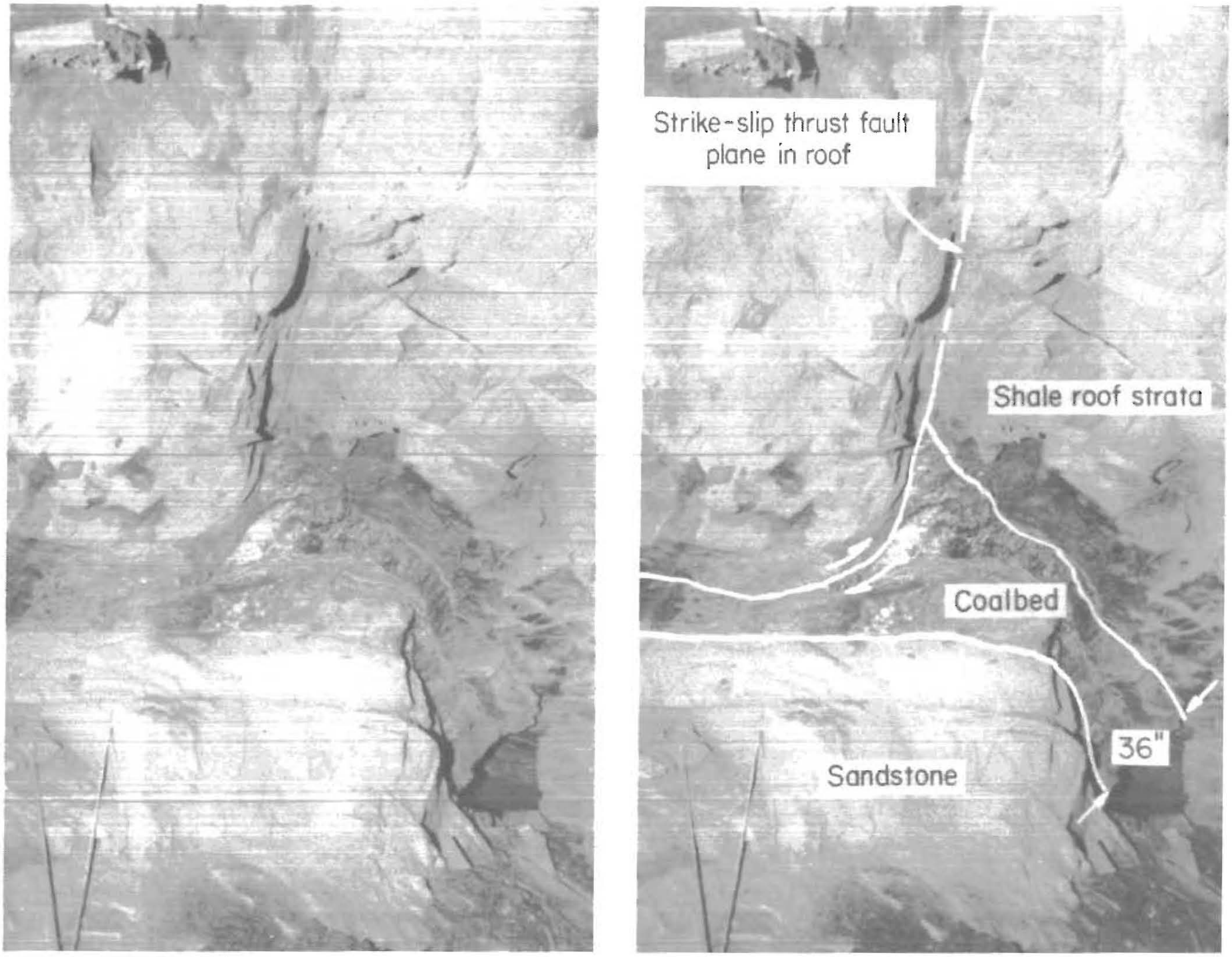

Figure 8.–Coalbed paralleled by bedding plane fault, which then shears into roof, causing roof fall.

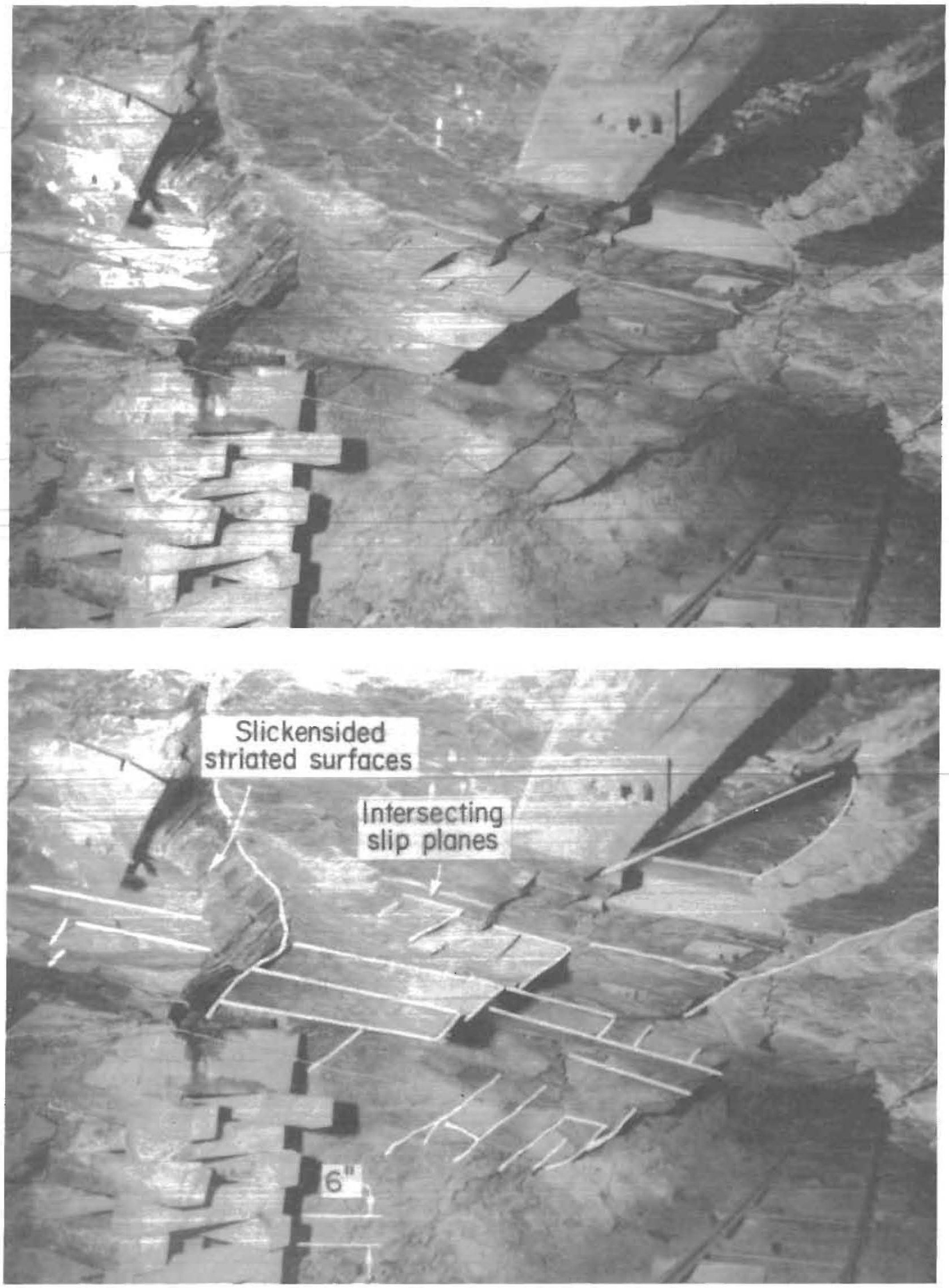

Figure 9.–Bedding plane fault exposed at coal-roof interface. Vertical fractures isolate hazardous roof blocks.

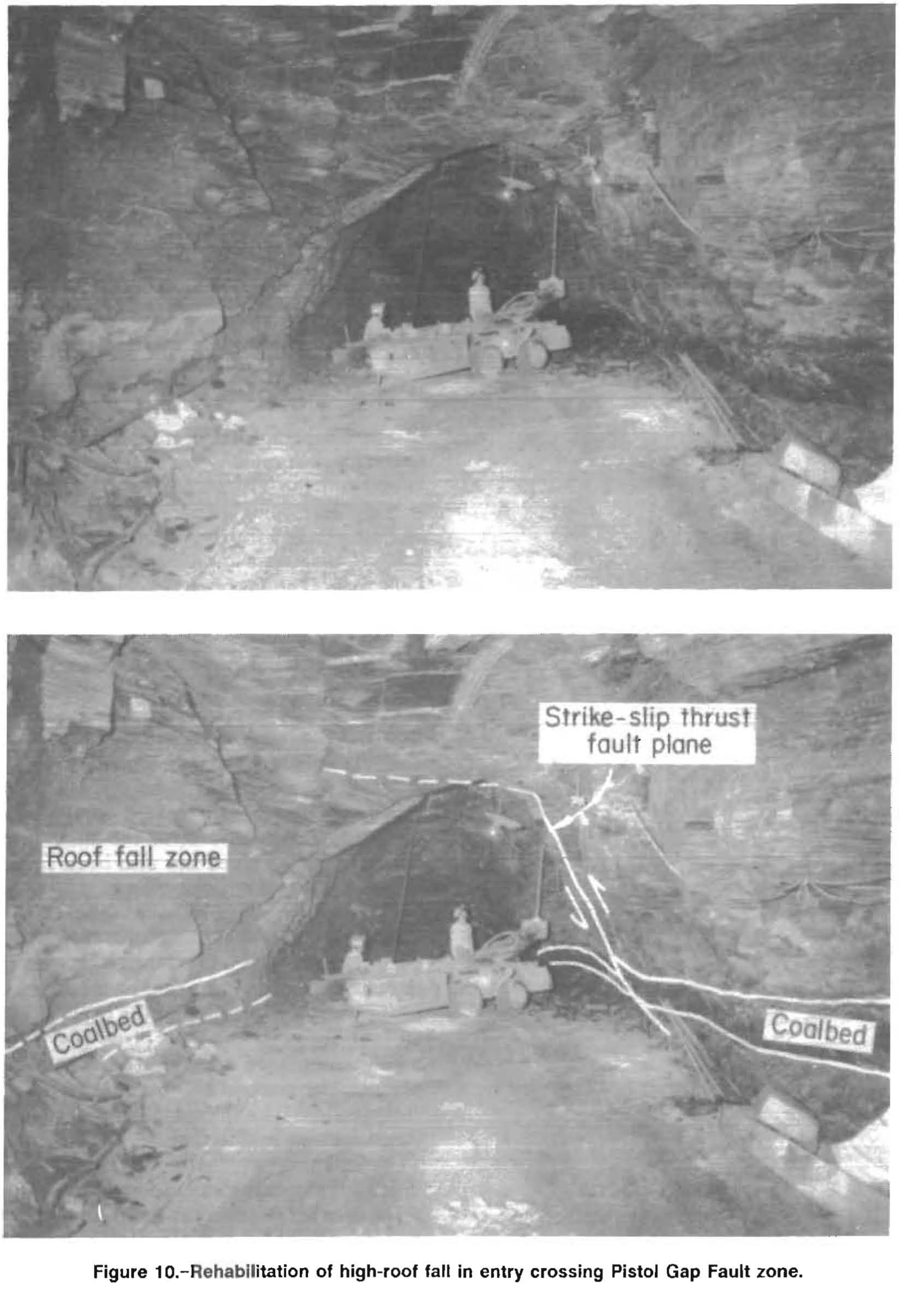

Figure 10.-Rehabilitation of high-roof fall in entry crossing Pistol Gap Fault zone.

Figure 6 (cross section B-B') also shows that the fault zone is accompanied by a swag zone up to about 75 ft wide where the coalbed is downbuckled approximately 8 ft. This feature is characteristic of compressional stress fields in both these cross sections and may serve to warn miners that they are approaching a fault. Figure 11 shows an interpretation of events in the formation of bedding plane faults at the site of the existing Pistol Gap Fault. Section A is the coalbed with the existing strike-slip fault; sections B-D are subject to increasing lateral compression until complete failure in section E. Section B shows the development of the swag, which precedes bedding plane failure in section C. In sections C and D, the severed coalbed is telescoping past itself as the thrust fault shears upward into the roof. The strike-slip fault plane is also deformed. Continued compression also warps the coalbed in the vicinity of the vertical failure.

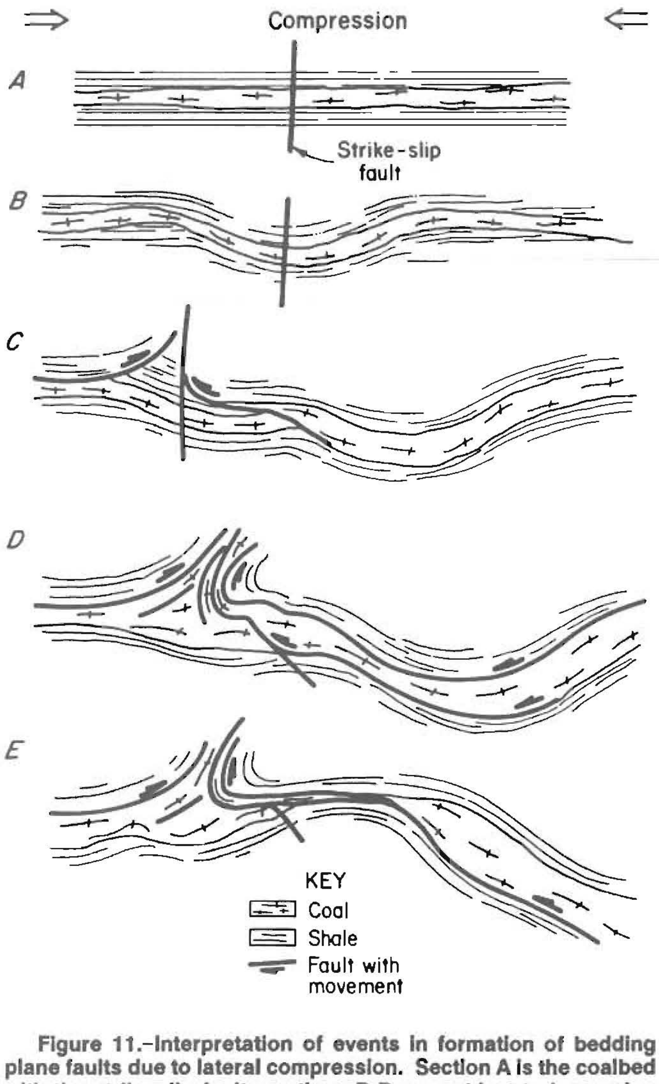

Figure 11.–Interpretation of events in formation of bedding plane faults due to lateral compression. Section A is the coalbed with the strike-slip fault; sections B-D are subject to increasing lateral compression until complete failure in section E.

The Falcon Fuel Mine intersects the Pistol Gap Fault in several other locations (fig. 5). At location E, an 11-entry section intersected the fault, which trends N. 36° W. Roof conditions were too poor to continue and the section was stopped.

When these faults are intersected, the operator usually has no idea how far the fault zone might extend. Generally, the fault is probed laterally with a continuous miner for a break to see if the fault can be easily crossed. If not, the section may be stopped and development can continue elsewhere if an acceptable place exists. At location C, it was necessary to drive through the fault zone to reach other reserves (fig. 5). This procedure was both time consuming and costly.

CHAPARAL MINE

The Chaparal Mine is another contract mine to United Co. This drift mine works the Jawbone Coalbed and has intersected the Pistol Gap Fault while driving a southwestern development (fig. 4). Figure 12 shows two cross sections through the fault zone. Cross section A-A' shows a large swag zone (approximately 230 ft wide) inby the fault zone. The Jawbone Coalbed has been buckled down 4 to 5 ft before returning to normal elevation outby the faults. As in the Falcon Fuel Mine, compression that oriented northeast-southwest caused a swag to the southwest of the fault zone. The coalbed failure is evident because a bedding plane fault exists at the coal-roof interface and between the roof and floor (fig. 13). This bedding plane fault then ramps up into the roof, causing a roof fall. The coalbed has been smeared out to only several inches thick. Also, there is a well-defined fault gouge zone that marks several of the fault planes within the coalbed. The coalbed has also been rippled, as seen on the outby side of cross section A-A' (fig. 12). This local "thin skinned" rippling is a common compressional feature.

Cross section B-B' shows the same failure reaction to compression. The outby block has been buckled up and the inby block has been split by the outby block (fig. 12), causing upward thrusting of the coalbed into the roof and an overturning of the fault plane (fig. 14). The coalbed and the roof strata are highly disturbed between the fault planes. The coalbed also thickens to over 93 in owing to compression. This thickening seems to be characteristic of thrust faulting in this area.

To minimize production loss and hazardous roof conditions, the operators were forced to narrow the development in order to cross the fault. In addition, fewer crosscuts were turned, which made pillars over twice as long as normal. Again, the narrow development causes restrictions to ventilation. Roof conditions were very poor in the 100- to 150-ft-wide fault zone. Most of the entries crossing the fault were inaccessible because of dangerous roof. Several falls were over 15 ft high and had to be supported by elaborate terraced cribbing (fig. 15). Within the fault zone, numerous intersecting fault planes broke the roof into blocks and made rock bolting ineffective.

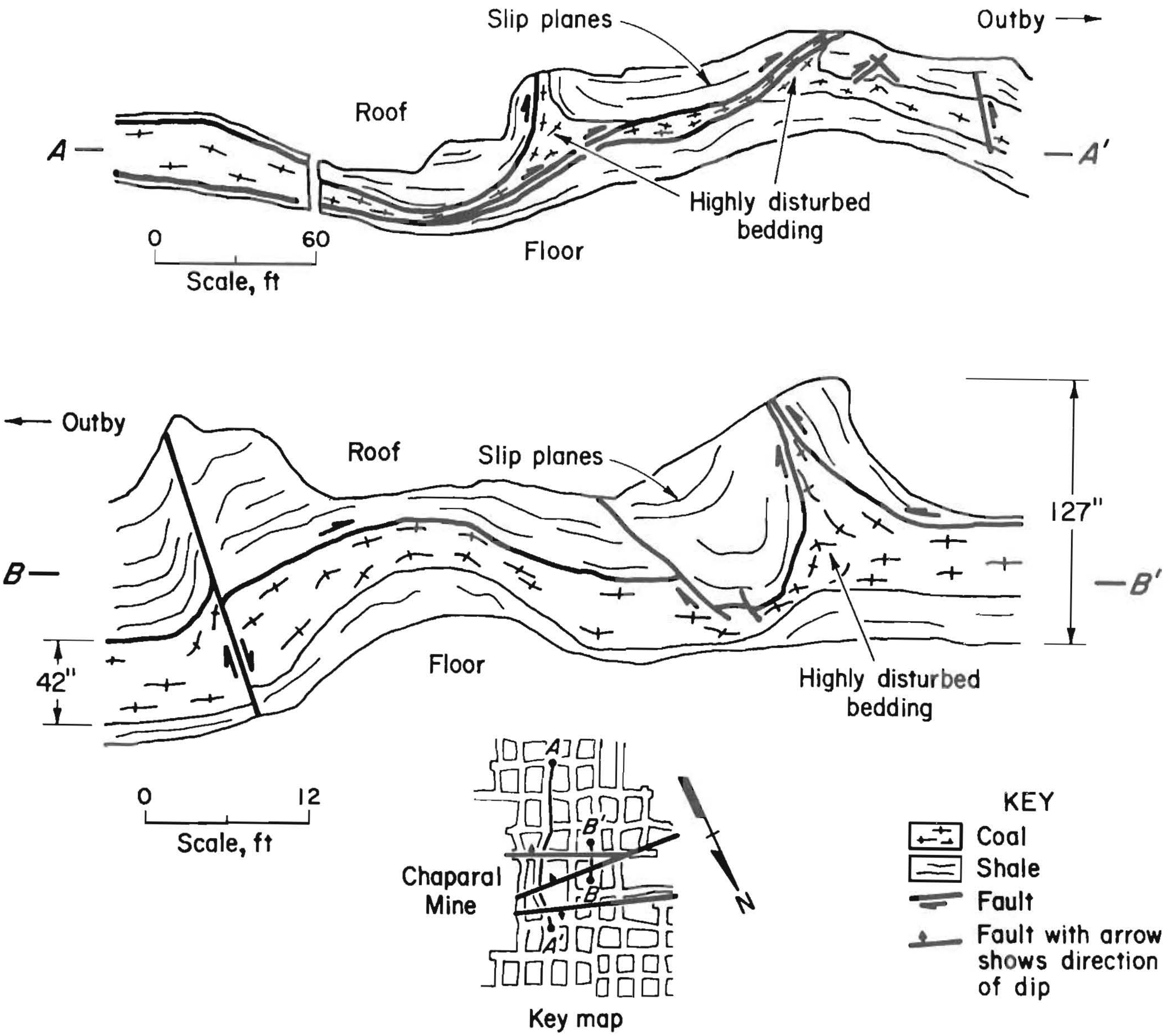

Figure 12.-Cross sections of Pistol Gap Fault exposure in Chaparal Mine.

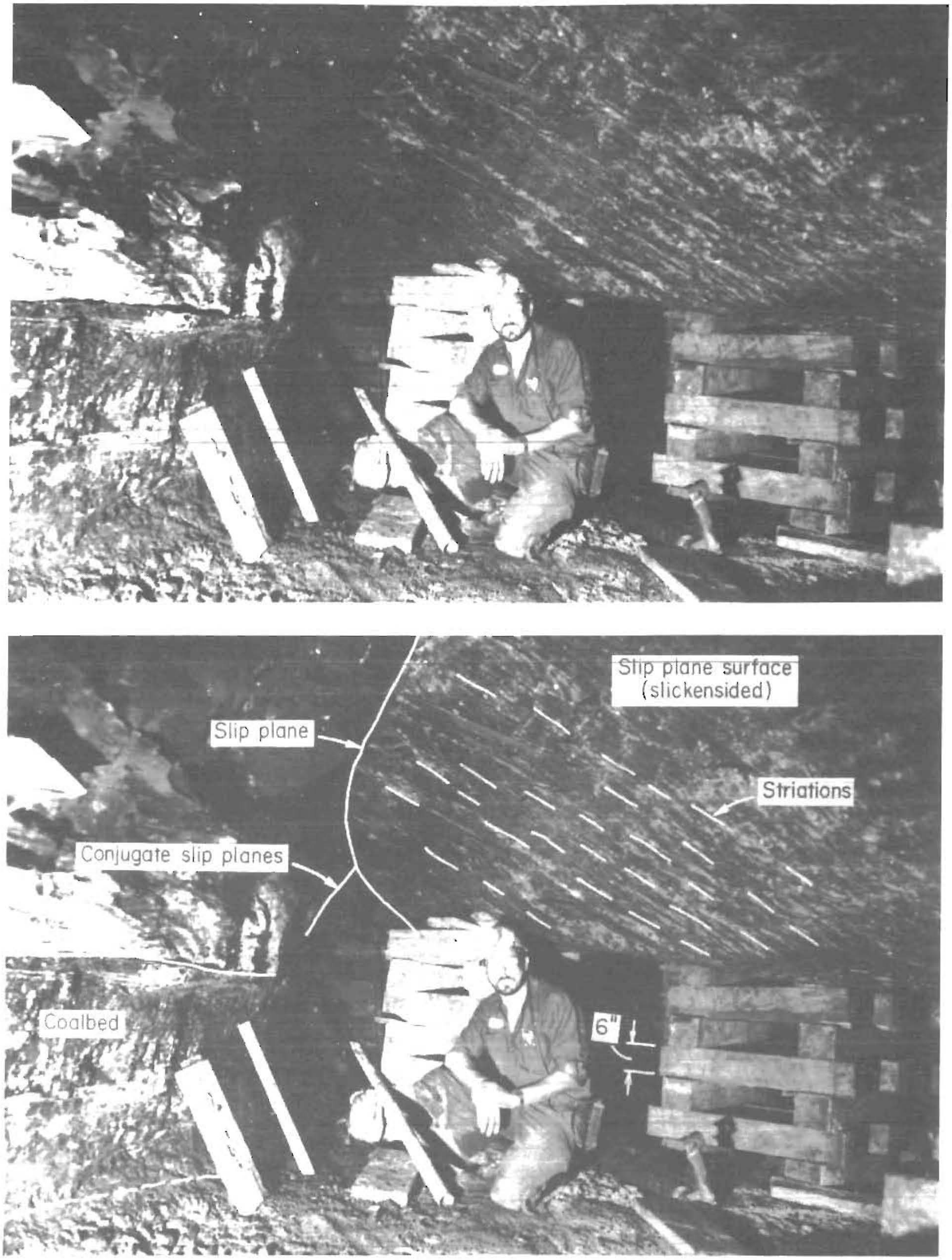

Figure 13.–Bedding plane fault rising into roof, showing roof fall caused by section of roof spalling away from fault plane.

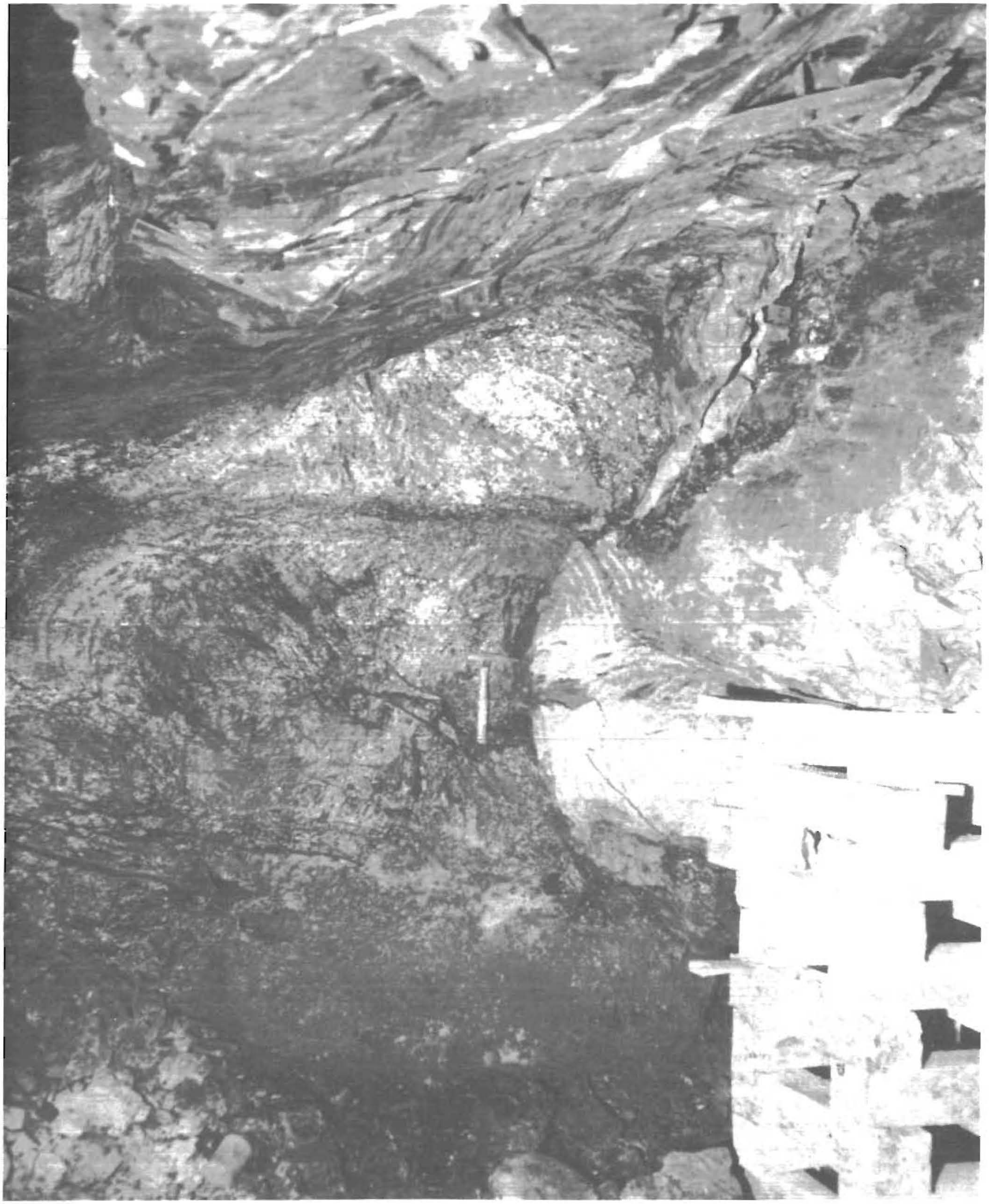

Figure 14.–Jawbone Coalbed split by compression along Pistol Gap Fault, with top half riding up into roof and bottom half pushed into floor.

Figure 15.-Two-tiered cribbing platform, built to support high-roof fall in Chaparal Mine.

STREET AND WHITED MINE

The Street and Whited Mine is located in the Jawbone Coalbed and butts up against both the Chaparal and Lisa Lee Mines (fig. 4). Operating with a 15- to 20-person work force, it is now a full-retreat operation because of its intersection with the Pistol Gap Fault.

The mine intersects the fault in two places (figure 16, location A and cross section A-A'). A southern driving, seven-entry section intersected the fault at cross section A-A'. The operators tried to cross the fault with two entries, but the coalbed pitched upward into the roof at a 30° angle. The mining machine was unable to mine at such a steep angle, and production was halted. Roof conditions began to deteriorate in the two advancing entries, with large roof falls developing. A bedding plane fault is evident at the roof-coal interface. A series of small thrust faults also splinter off the bedding plane fault and enter the roof shales. These fractures indicate compressional failure.

There is no swag zone on the northeastern side of the fault as was seen at the Chaparal and Falcon Fuel Mines. Also, unlike the other mines where the coalbed rises abruptly into the roof, the coalbed at Street and Whited Mine rises on a gradual 6-pct grade. The coalbed also maintains its full 42-in height and has not shown signs of thinning or thickening. Possibly, if the fault had been further exposed, these features may be seen. Because of limited reserves on the southwestern side of the fault zone, the operators have decided not to attempt to cross the fault zone. The other location where the mine intersected the fault is in the main entry just inby the mine portal (figure 16, location A). Here, the disturbance is limited to merely a 6-in normal type of offset and a rippled coalbed.

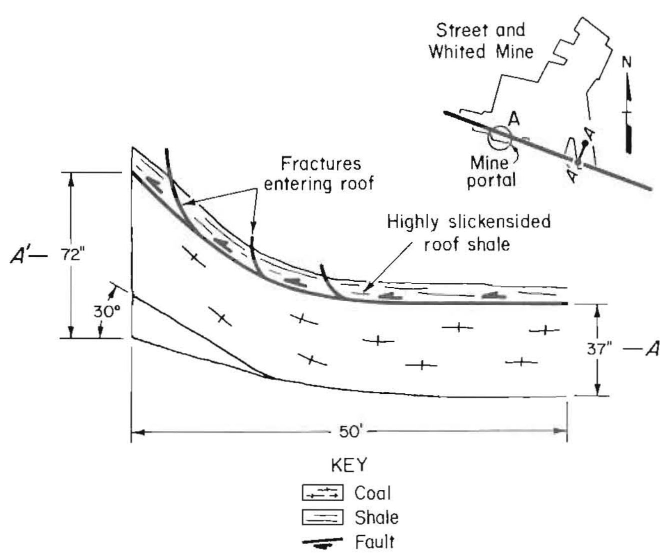

Figure 16.–Cross section of mine entry intersecting Pistol Gap Fault at Street and Whited Mine.

AJ AND A MINE

The AJ and A Mine is located in the Red Ash Coalbed, approximately 170 ft above the Jawbone Coalbed. This mine is a small, five-person operation and a contract mine to United Co. At least seven different operators have attempted to work this mine. All the failures have been directly related to the effects of the Pistol Gap Fault on roof conditions. The mine is located on the fault trace, between the Falcon Fuel and Chaparal Mines (fig. 4).

Figure 17 is a cross section of the Pistol Gap Fault as it is exposed by mining. The total offset of the coalbed is 96 in. This apparent offset is due mainly to the coalbed being downbuckled in the inby direction because of compression. After downbuckling, the coalbed was sheared off by a bedding plane fault running along the floor, which then cut upward through the coal. The fault runs along the top of the coalbed, smearing the coal to 2 in thick before cutting up into the roof and overturning (fig. 18). Parallel thrust faults are also seen in the inby roof shales. Another opposite-dipping thrust fault is seen on the outby side of the fault zone (fig. 17). This fault flattens to a bedding plane fault and runs along the coal-roof interface. The overlying roof shales are highly contorted and disturbed as though dragged along above the fault plane and resisted by the coalbed. The presence of two opposite-dipping bedding plane-thrust faults shows failure on both sides of the fault zone. The coalbed itself shows signs of slippage and disturbance, and becomes overthickened as the fault enters the roof. On the southwestern side of the fault, there is an area where the floor is buckled up, causing the overlying coal to thin. The roof shows tensional fractures where the coalbed is squeezed (fig. 17). The affected zone is 50 to 75 ft wide and was accessible in only one entry. Where the coalbed sharply rises, there is a roof fall about 7 ft high. Numerous vertical roof slips are present that do not disturb the coalbed. At this mine, failure has occurred along bedding from both the southwest and the northeast. The AJ and A Mine, which is stratigraphically higher than the other study mines, intersects the fault directly in line with its linear trace (fig. 4). This indicates that the Pistol Gap Fault plane is vertical and planar.

LISA LEE MINE

The Lisa Lee Mine, another contract mine to United Co., has been severely affected by the Keen Mountain Fault and a local spur fault, possibly related to the Keen Mountain Fault (fig. 4). Four development sections have intersected fault traces, and a fifth set of entries are expected to intersect a fault in the near future.

At location A, a five-entry section being driven southeast was stopped when the coal was interrupted by a suspected fault (fig. 19). The Jawbone Coalbed thickened up to 96 in. in one entry and 86 in. in another entry adjacent to the disturbance. (The coal height is normally 28 to 33 in at this mine.) The coalbed then abruptly ended.

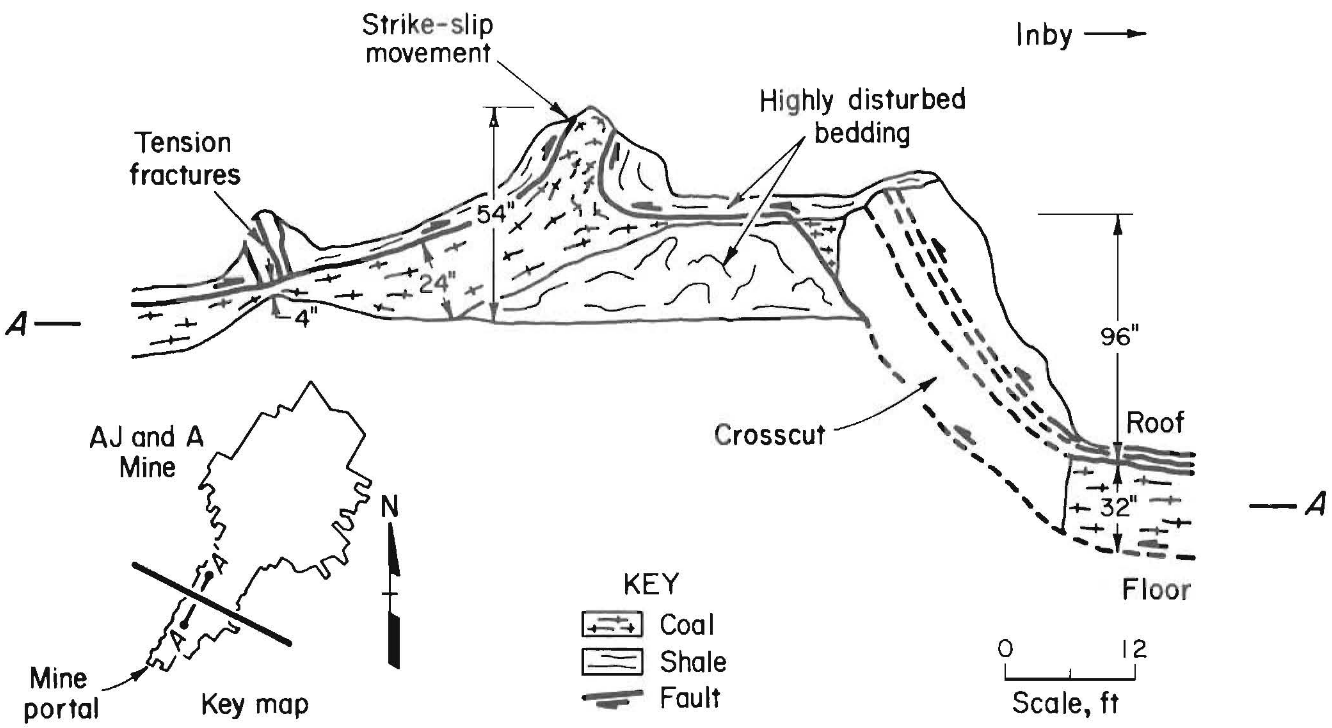

Figure 17.–Cross section of Pistol Gap Fault at AJ and A Mine.

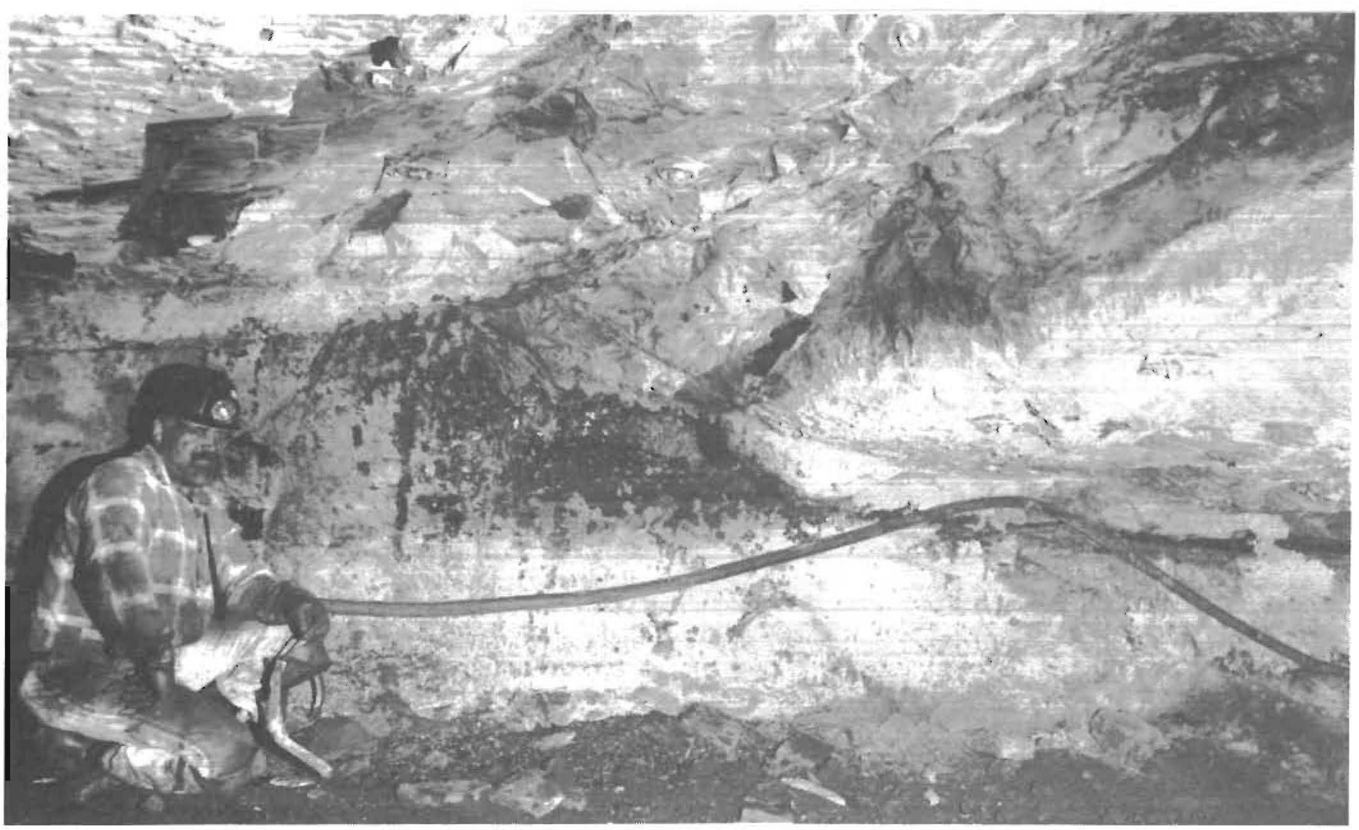

Figure 18.–Pistol Gap Fault exposed in rib at AJ and A Mine.

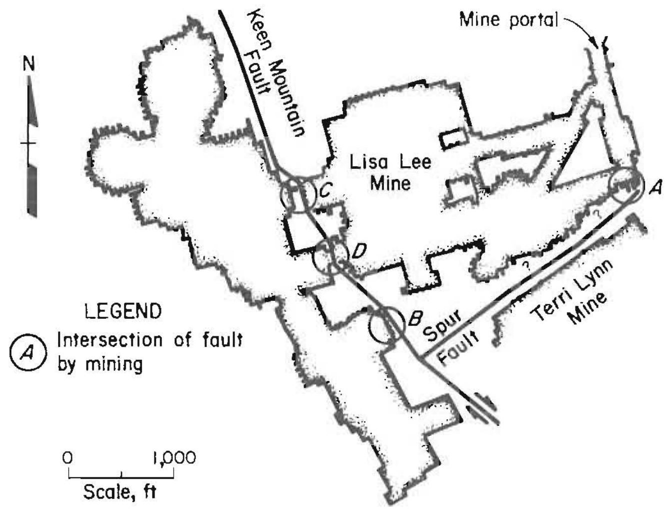

Figure 19.–Lisa Lee Mine outline and areas (circled) affected by Keen Mountain Fault.

Although the section is now flooded and inaccessible, it is suspected that the coal on the southeastern side of the fault was thrust up against and over the northwestern block, causing the overthickening. This type of overthrusting is found on other low-angle bedding plane faults in the area. Figure 19 shows that this inferred fault follows a corridor between the Lisa Lee Mine and the Terri Lynn Mine, which is located directly to the southeast and continues to adversely affect the Lisa Lee Mine along its southern border.

The Keen Mountain Fault is intersected by the Lisa Lee Mine in four places. The northeastern driving section at location B was completely stopped when it intersected the fault (fig. 19). The coalbed "ran out," and no attempt was made to drive through the zone and relocate the coal. At location C, a six-entry development was narrowed to one entry in crossing the fault. This single entry causes a severe restriction to ventilation. In addition, poor roof conditions occur at this fault intersection. The Keen Mountain Fault continues northwest through location C but is not again exposed because the Jawbone Coalbed splits are too thin to mine.

At location D (fig. 19), the Keen Mountain Fault intersects mains, which provide access to the western side of the mine. Here, an eight-entry development was necked down to three entries to cross the fault zone. The effects of the fault were mapped in detail at this crossing. Figure 20 shows part of the fault zone in cross section at location D. The zone is approximately 200 ft wide and consists of a bedding plane thrust fault and numerous roof fractures, which do not offset the coalbed, and a large coalbed swag. The main coalbed offset is 48 to 51 in, and the bed is downbuckled to the northeast. The main fault runs along bedding on the northeastern side of the offset for an undetermined distance until it abruptly enters the roof (60°), causing a 3-ft-high fall of roof. Figure 21 shows the bedding plane fault and the associated roof disturbance. Numerous horizontal slickensides and polished surfaces indicate extensive slippage between the coal and immediate roof shales. Compression in a northeastern-southwestern direction has caused the coalbed to be dragged up into the roof and locally thickened (over 72 in). Slippage within the coalbed is apparent, and bedding is highly disturbed. The adjacent roof shales are also highly distorted. Failure occurred along the roof-coal interface and also along the bedding planes within the coalbed (fig. 21).

EFFECT OF FAULTING ON OTHER COALBEDS

Seven coalbeds in the study area have been heavily mined and are affected by the Keen Mountain and Pistol Gap Faults. All coalbeds are above drainage and are worked mainly by small operations (5- to 20-person). Mining in the Kennedy Coalbed is shown in figure 22. At location A, the Keen Mountain Fault offsets the coalbed by 6 ft (*8*). The affected zone is 200 ft wide and shows the characteristic swag on the southwestern side. At location B, the same feature truncates another mine. The swag is also on the southwestern side of the fault.

The Splashdam Coalbed is stratigraphically the highest coalbed being mined in the study area. In several instances, the Keen Mountain Fault has affected mining in this coalbed (fig. 23). In addition, the type of displacement varies between tensional, compressional, and shear movement. At location A, the coalbed is displaced 3 ft with a swag on the southwestern side. The offset is a normal tensional break with the southwestern side downdropped. At location B, the fault does not offset the coalbed but occurs as a swag, approximately 200 ft wide. The coalbed has not failed here but has only been downbuckled. This indicates not only the intensity but that the type of movement on the fault has changed in slightly over 1,000 ft. At location C, the fault was exposed in a strip mine highwall. This offset was a normal tensional break with about 3 ft of offset (figure 23, western side downdropped). The fault was actually a zone about 200 ft wide with zones of vertical fractures spaced every 20 ft. There is another highwall exposure of the fault shown in figure 24. Here, the offset is a normal tensional offset of about 18 in.

The Keen Mountain Fault appears to have a much larger displacement at greater depth from the surface (>1,500 ft deep). The Pocahontas #3 Coalbed at Island Creek Coal Co.'s Beatrice Mine (now closed) had been displaced up to 18 ft by the fault (*5*) (fig. 25). Preliminary seismic information from above Consolidation Coal Co.'s Buchanan No. 1 Mine, also in the Pocahontas #3 Coalbed, indicates up to 20 ft of displacement (*9*). At all exposures, strike-slip movement is indicated by slickensides and fault gouge.

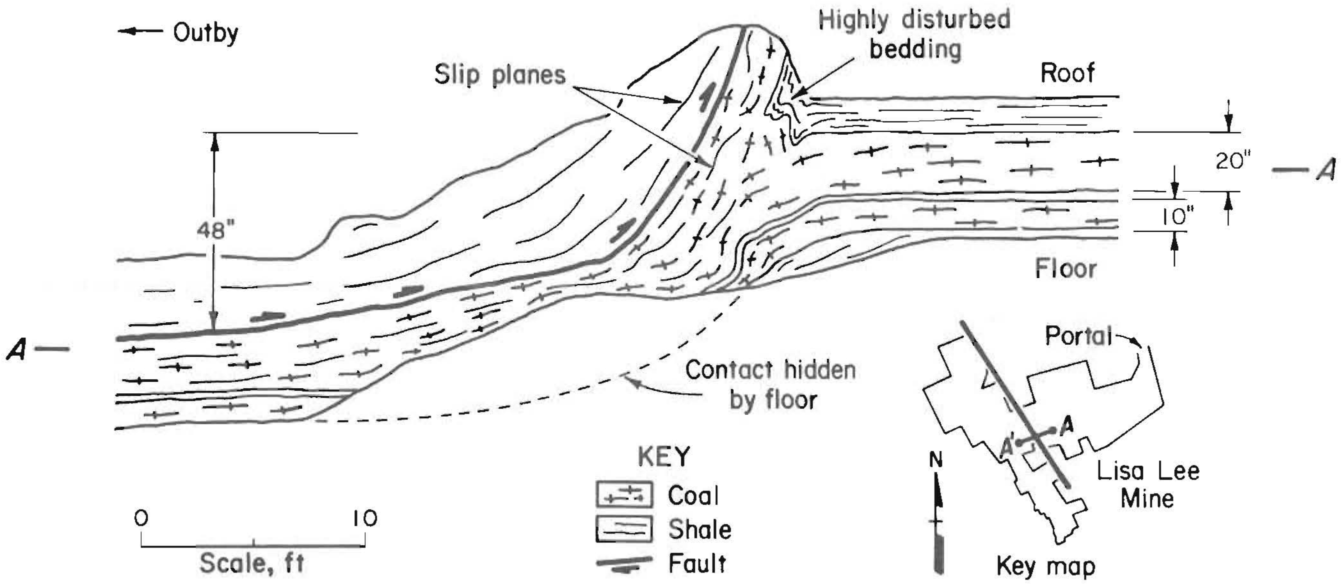

Figure 20.-Cross section of mining exposure of Keen Mountain Fault at Lisa Lee Mine.

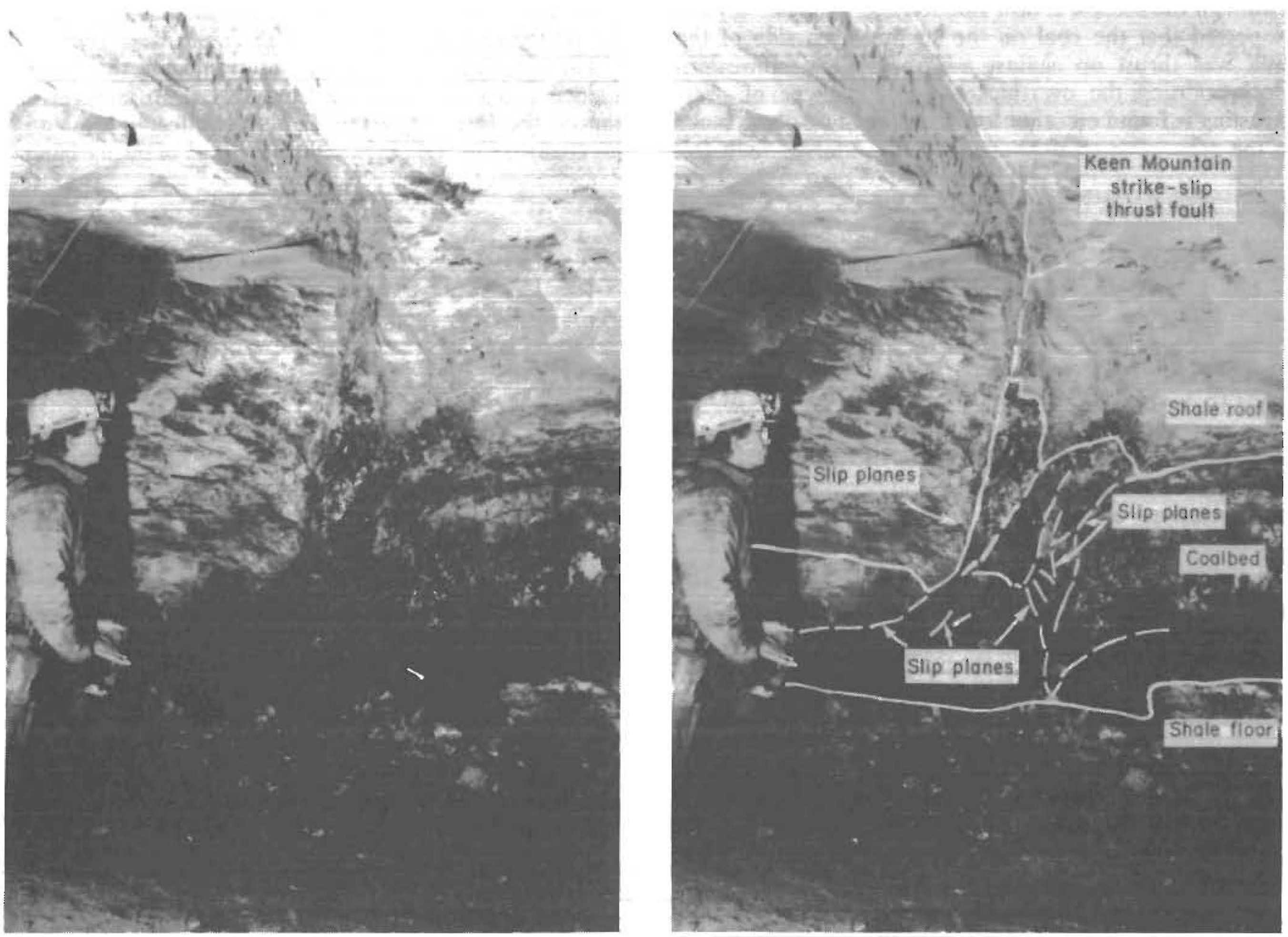

Figure 21.-Exposure of Keen Mountain Fault zone in Jawbone Coalbed, showing disturbed coalbed with fault plane entering roof.

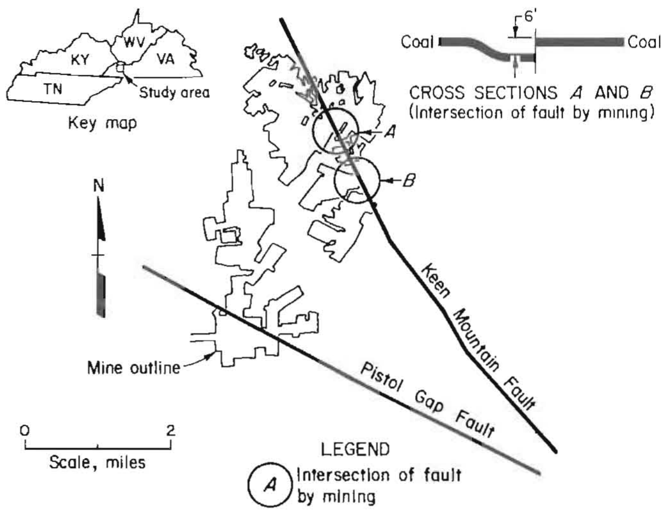

Figure 22.–Extensively mined Kennedy Coalbed affected by Pistol Gap and Keen Mountain Faults.

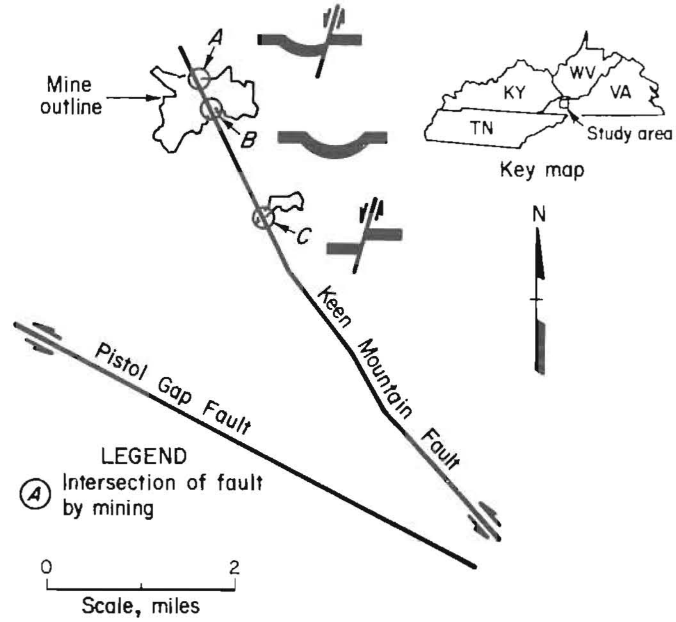

Figure 23.–Exposures of Pistol Gap and Keen Mountain Faults in mined-out Splashdam Coalbed.

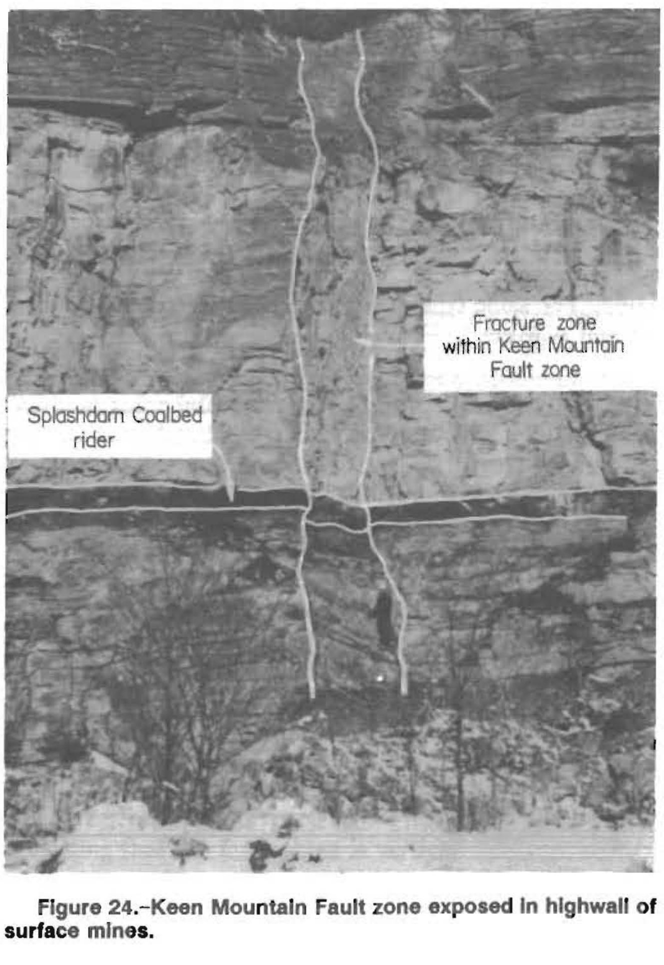

Figure 24.–Keen Mountain Fault zone exposed in highwall of surface mines.

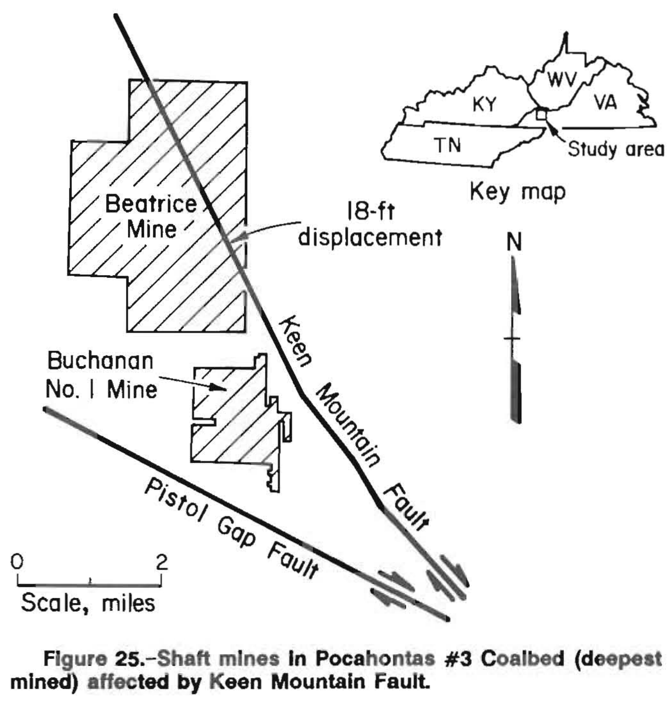

Figure 25.–Shaft mines in Pocahontas #3 Coalbed (deepest mined) affected by Keen Mountain Fault.

INTERPRETATION OF EVENTS IN FORMATION OF THRUST FAULTS IN STUDY AREA

Evidence of both strike-slip movement and thrust faulting at the underground exposures of the Keen Mountain and Pistol Gap Faults indicates two episodes of faulting. Strike-slip movement indicated by horizontal slickensides on vertical fault planes at all underground exposures of these two faults is likely a result of the original northwestern compressional field, which created the Pine Mountain overthrust sheet to the southwest of the study area. While the Pine Mountain sheet became completely detached by the compression, the rock strata on the northeastern boundary was only partially isolated by the development of tear faults [(Keen Mountain, Jess Fork, Pistol Gap, and Little Paw Paw (fig. 4)]. These may represent the first phase of sheet formation adjacent to the Pine Mountain sheet, even though complete detachment did not occur. The movement on the faults is right lateral, which is consistent with the northeastern-southwestern compression (*4*).

The second phase of faulting on the Keen Mountain and Pistol Gap Faults is indicated by bedding plane and thrust faulting. These compressional features, previously described, are the result of a reorientation of the stress field to a compressional field oriented northeast-southwest. This stress may have been generated by a rotation of the Pine Mountain overthrust sheet (*3*).

Figure 26 is an interpretation of the two stages of faulting believed to have occurred on the Pistol Gap and Keen Mountain Faults. Figure 26*A* shows simple strike-slip movement as a result of northwestern-southeastern compression. Figure 26*B* shows later bedding plane faults and deformation as a result of compression due to rotation of the Pine Mountain sheet. A northeastern-southwestern compressional stress field caused thrust faulting to occur along weak interfaces (bedding planes and coalbeds). The Pistol Gap and Keen Mountain Faults are the points at which compressional stress was relieved by vertical coalbed failure, as seen in the Chaparal Mine and the Falcon Fuel Mine. The same type of failure is seen 170 ft higher in the AJ and A Mine.

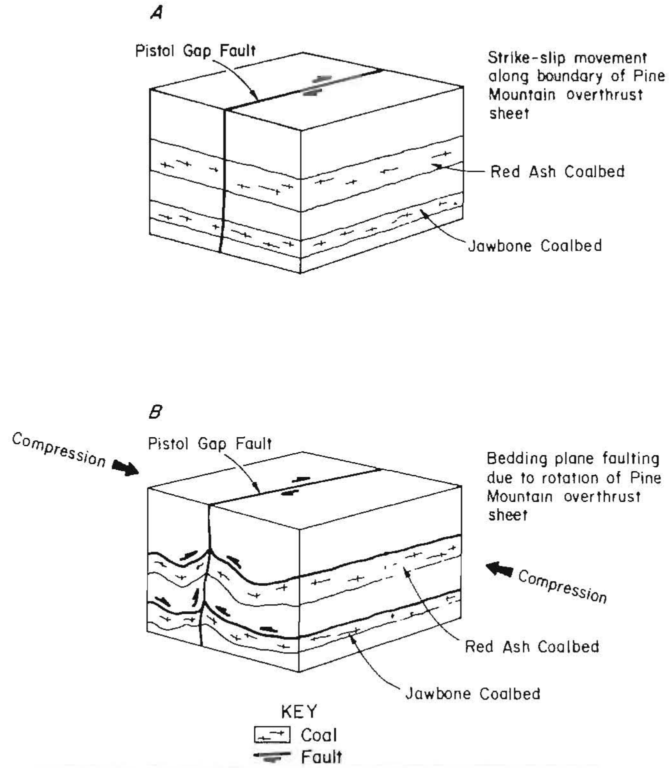

Figure 26.–Block model showing sequence of coalbeds subjected to lateral forces, causing coalbed buckling and bedding plane and vertical failure at Pistol Gap and Keen Mountain Faults.

ECONOMICS OF MINING THROUGH FAULT ZONE

Mining through a fault zone to gain access to additional coal reserves can be expensive. The loss of coal production, as well as the cost of additional roof support, supplies, and equipment repair increase the operating cost and consequently decrease profits. The following is a calculation of the estimated cost of mining through a fault zone based on information obtained from Permac Inc., Falcon Fuel Coal Co., Chaparal Coal Co., and Lisa Lee Coal Co.

BASIS OF COST CALCULATIONS

The calculation of net profit or loss was based on coal-noncoal production under normal mining conditions (coal-producing) and fault zone conditions (noncoal-producing). The following assumptions are made to obtain mining cost for a drift-mouth operation: 36- to 48-in coalbed, room-and-pillar design, one continuous miner section, and one 8-h shift, 5 days per week.

Factors used to calculate the net profit or loss for the two conditions are as follows:

Average production per 8-h shift . . st . .	408
Average selling price per short ton	$8.40
Average operating cost per 8-h shift . . .	$3,084.00

Normal conditions.–The net profit is calculated by subtracting the operating cost from the gross revenue (short tons produced times selling price), as follows: [(tonnage) X (selling price)] - (operating cost) = net profit, or (408 X $8.40) - $3,084.00 = $343.00 per 8-h shift.

Fault zone conditions.–Assuming that the fault zone is 200 ft wide, similar to that measured in this study, the net loss from mining through the fault zone would be 6.6 days multiplied by the operating cost and the net profit per 8-h shift. The 6.6 days are derived by dividing the 200-ft-wide fault zone by 30 ft/d entry advancement (200 ft ÷ 30 ft/d = 6.6 days) per 8-h shift. The net loss when mining through a fault zone is directly dependent on entry advancement. It was found that normal entry advancement by one working section in an 8-h shift was approximately 225 ft. In a fault zone, entry advancement decreased to about 30 ft per 8-h shift. This is an 85-pct decrease in the rate of entry development. Mining through a fault zone results in an average net loss of $22,619.00. Average net loss is determined as follows: [(days) X (operating cost)] + [(net profit) X (days)] = net loss, or (6.6 X $3,084.00) + ($343.00 X 6.6) = $22,619.00 per 8-h shift. This represents a conservative estimate. Several coal companies reported net losses ranging from $16,500.00 to $200,000.00 when mining through a 200-ft-wide fault zone. An advancing section of the Street and Whited Mine was halted because of its intersection with the Pistol Gap Fault. The cost of mining through the fault would have exceeded the revenue expected from the small coal reserves remaining on the other side of the fault zone.

ADDITIONAL COSTS

Additional expenditures, not included in the normal operating costs, that could be incurred when mining in a fault zone include additional roof support, modifications in ventilation, and inundation of water.

Supplemental roof support is necessary, especially in haulage or travel areas. The highly fractured and slickensided roof associated with fault zones is difficult to support with just normal bolting patterns using mechanical bolts. The additional cost of adding cribs and crossbars and/or resin bolts could be justified when compared with the potential cost of cleaning up and rebolting a roof fall area later. The cleanup cost could be even more expensive if the roof fall stops coal production by blocking haulage or tying up production equipment.

Modifications in mine ventilation could also add expenses to operating costs. It may be necessary, because of cost and danger, to reduce the width and number of the entries when mining through a fault zone. This change in entry development may require a reconfiguration of the ventilation in order to supply adequate air beyond the fault. Changing existing stoppings and overcasts would add labor and new material costs. A reduction in size and number of entry openings could prevent adequate air volume and flow required to ventilate future mine development beyond the fault zone. Mine fans used by the coal mines in this study could cost between $30,000.00 and $60,000.00.

USING GEOLOGIC INFORMATION TO RECOGNIZE STRUCTURAL FAULTS AND ASSOCIATED GROUND CONTROL HAZARDS

Geologic discontinuities that affect a single mine or numerous adjacent mines may be related. The Falcon Fuel Mine intersected discontinuities on five separate occasions. Three of these occurrences involved the Pistol Gap Fault and two involved the Keen Mountain Fault. Without prior information, these discontinuities could be viewed as isolated and unrelated events. Figure 26 shows a possible interpretation for the structural event that caused the Pistol Gap Fault. Compression, probably related to the overthrusting and rotation of the Pine Mountain sheet, caused failure to occur along bedding planes between strata. Slippage occurred along bedding planes until the stress was relieved by vertical failure at pre-existing strike-slip faults. Bedding plane slippage continued to occur as the coalbed was thrust up into the roof. Observation of the Pistol Gap Fault in the Red Ash Coalbed above the Jawbone Coalbed indicates the vertical continuity of the faults, which can be used as a predictive tool. The affected part of the overlying AJ and A Mine lies directly along the projected Pistol Gap Fault trace, indicating that the fault plane is vertical.

The Keen Mountain Fault was formed in a similar manner. The Lisa Lee Mine encountered the Keen Mountain Fault in four places. This convincing example of linearity should warn prospective new operators of the high probability of encountering the fault along its trace. Operators mining in overlying and underlying coalbeds should be prepared to encounter the faults.

It would be nearly impossible to delineate this type of faulting from drill-hole information because the vertical displacement is so slight. Remote sensing imagery may show the features as lineaments. Both the Keen Mountain and Pistol Gap Faults are represented by lineaments plotted on Landsat imagery, although the Pistol Gap Fault is more prominent. The Keen Mountain Fault was first mapped by SLAR imagery as a 14-mile-long lineament (5). Lineament information may be used as a predictive tool to help demonstrate lateral continuity and to highlight lineament intersection, which may be particularly dangerous. Although this information is helpful, underground information is still necessary in order to determine the extent and nature of the potential disturbance. Collecting local mine map information is necessary in understanding the local geologic history of a coalbed. Equally important is underground observation for the recognition and interpretation of the geologic situation.

In order to make interpretations, it is essential to accurately sketch the fault or discontinuity zone. It is also necessary to clear debris from around the discontinuity, as well as rock dust from the rib, in order to see clearly. Accurate measurements of offsets, zone widths, and dip angles are necessary, and photographs are helpful. Interpretations, such as direction of movement, and rotation of fault blocks can then be made.

An indicator of approach to the Keen Mountain and Pistol Gap Faults is the swag or rolling down of the coalbed over a distance of 150 to 200 ft. The coalbed can dip down 8 ft or more. The swag appears on only one side of the fault, and so it may not be encountered, depending on the direction of mining. The fault movement is known to be variable. Offsets of 6 in to 18 ft have been observed. In several cases, the swag and bedding plane fault occur together. In other cases, the swag occurs alone. The compressive force may not have been great enough to cause the coalbed to fail, only to buckle. So in the case of these compressive bedding plane faults, if a significant swag is encountered, it may be an indication of the approach to a fault.

In a number of cases where the fault was mined through, the intersection of two or more opposite-dipping bedding plane faults caused the roof to drop out in blocks. These blocks should be supported by angle bolts, roof trusses, or straps to prevent arching falls. In all cases, the coalbed and surrounding draw slate and roof shales are severely disturbed. This disturbance is caused by compression and crushing of rock. Fault gouge is found along bedding plane faults and also vertically where the coalbed is dragged into the roof. This crushed rock has very low strength and should be avoided as a sole anchor for roof bolts.

ENGINEERING RESPONSE TO RECOGNIZED GROUND CONTROL HAZARDS

For mine planning purposes, the advantage of advance knowledge of existing faults is important. If the fault cannot be avoided, then its effects can be minimized by limiting the number of main entries that cross the fault zone. Provided they are located far enough from the zone to avoid poor roof conditions, submain entries can be driven parallel to the fault zone, and short panels can be mined toward the fault zone until conditions become nonproductive or hazardous. Where necessary to cross the fault zone, the headings should be turned at right angles to the trace of the fault to minimize the exposure to the fault. Also, long pillars should be cut through the zone before driving a crosscut. Because these crossings will be used for haulage or access, heavy permanent support (crossbars, tunnel liners, etc.) should be installed. The width and number of entries may need to be reduced to maintain their integrity, but entry design must also be adequate to maintain enough airflow and volume for future mine development. Blasting to drive through a fault zone could minimize net losses. The blasting could be done with a minimum crew on weekends or during downtime in a coal-producing section. This also protects the miner from damage that may occur when rock is cut with a mining machine.

By using appropriate roof support when mining through a fault zone, mine operators can avoid hazards, costly clean up, and rebolting of roof failures. It was found that the most common supplemental supports are cribs used in conjunction with cross collars (4- by 12-in wood planks) (fig. 27). Point anchor resin or other resin-assisted bolts can be used in fragmented roof. Also, angle bolting or truss sets can be used to hold roof members together. Crossbars, steel mats, or wire mesh used in conjunction with bolts decrease spalling of immediate mine roof. Large slip or fault planes disrupt the lateral continuity of the immediate and sometimes main roof. These conditions are most severe when these structures are orientated parallel or subparallel to the direction of mining. With this type of orientation, the mine roof may be segmented into cantilever beams. The cantilever effect can be reduced by bolting and strapping together the roof on each side of the slip or fault plane to form an integral built-in beam (fig. 28). Angle and orientation (strike and dip) of the slip or fault plane should be considered when determining the length and angle of installation of the roof bolt.

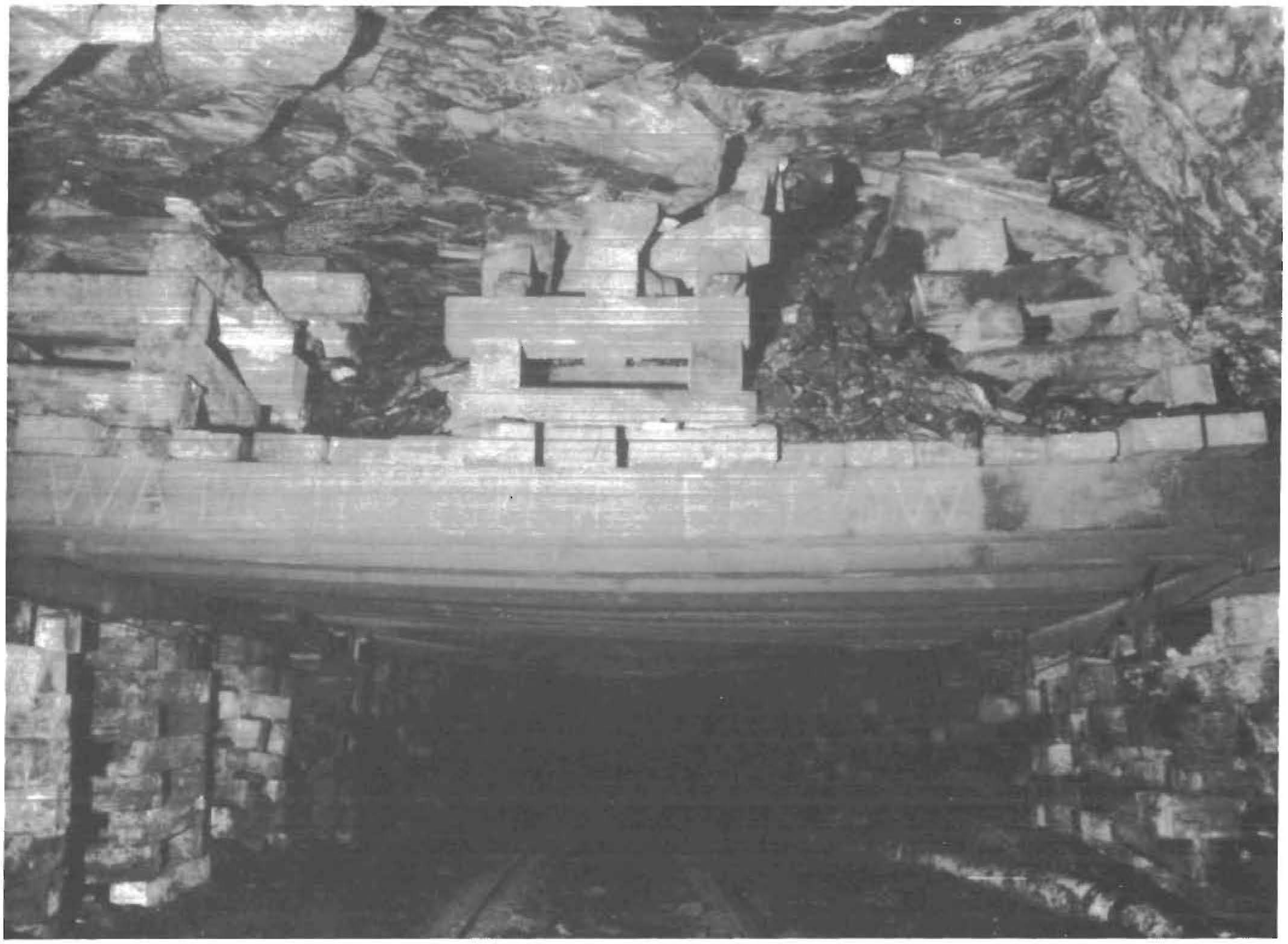

Figure 27.-Permanent structure used to support roof through fault zone.

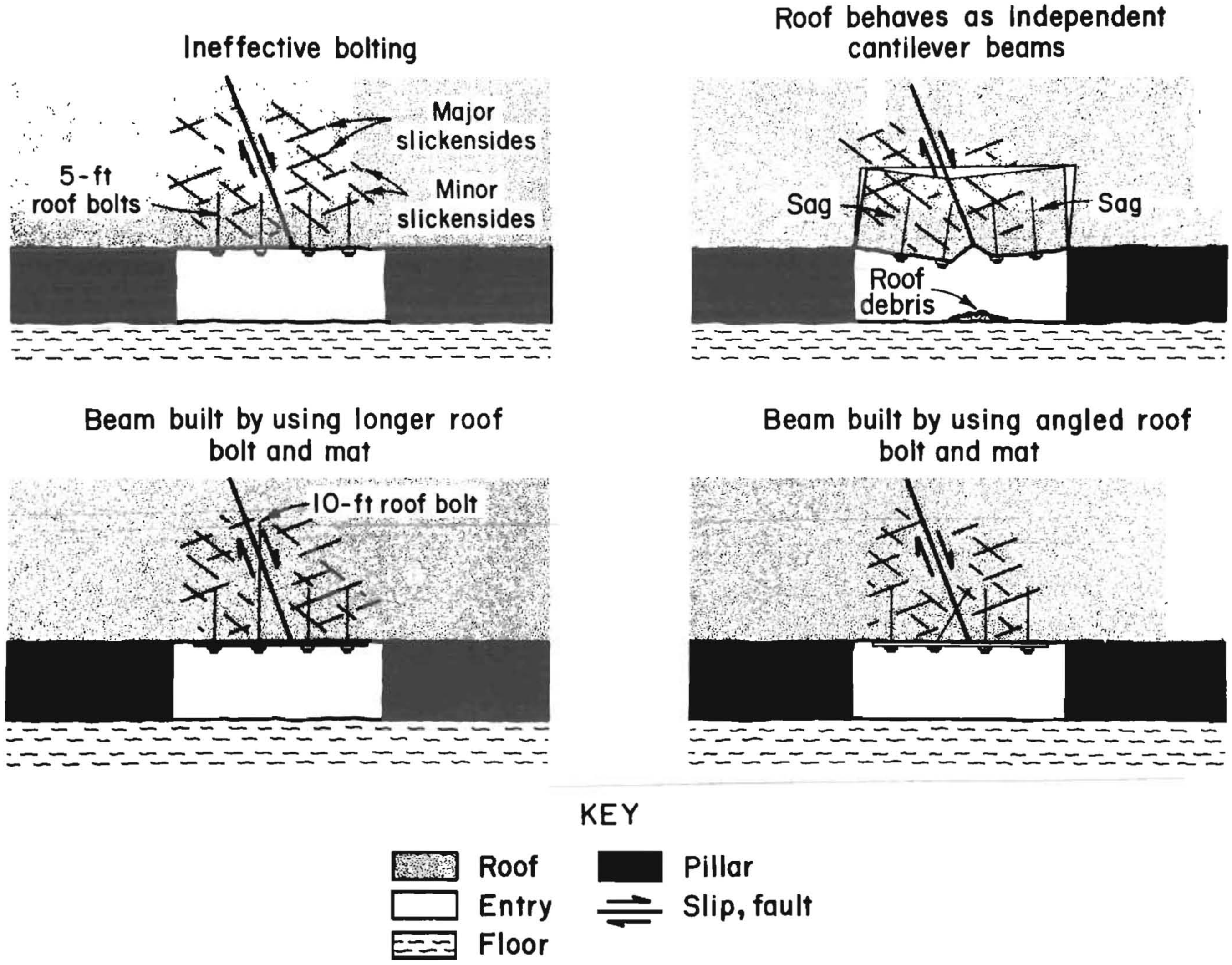

Figure 28.–Supports used in steeply inclined fault plane in roof.

SUMMARY AND CONCLUSIONS

The Keen Mountain and Pistol Gap Faults have been identified as strike-slip faults caused by crustal tearing along the margin of the Pine Mountain overthrust sheet. These faults severely affect roof quality in numerous coal mines in Buchanan County, VA. Fault exposures in five mines and two coal seams reveal fault zones up to 200 ft wide, offsets up to 18 ft, coalbed swags up to 15 ft, and roof falls up to 20 ft high. The displacement on the Keen Mountain Fault appears to increase with depth. Up to 18 ft of offset has been documented at approximately 1,500 ft deep. The Pistol Gap Fault was found to be vertically continuous between coalbeds. The recognition of these faults as linear discontinuities across several mines can be accomplished by the observation, description, and mapping of the type and nature of fault movement. Recognition criteria include compressional features such as obvious slip planes between roof, floor, and coalbed; fault gouge; severed coalbeds telescoping past themselves; and swag zones or rippled or folded bedding planes. This information, in conjunction with Landsat imagery and regional mine map information, is essential to prediction of a fault occurrence. Once anticipated, faults can either be avoided or appropriate mine design changes or support changes can be made.

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